Transport Theory for Propagation and Reverberation

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LONG-TERM GOALS

Development of computationally efficient modeling methods for shallow water propagation and reverberation that can account for the effects of multiple forward scattering from waveguide boundary roughness and volume heterogeneity such as internal waves.

OBJECTIVES

In FY11 our shallow water propagation model based on transport theory was extended to include reverberation, and it was found that sea surface forward scattering could have very important effects on reverberation level at mid frequencies, e.g., at 3 kHz. One objective in FY12 was to obtain some experimental verification of these important effects based on existing data. (A reverberation experiment planned for FY13 (TREX13) is being designed to give a more definitive verification.) An additional objective in FY12 was to use transport theory results to support the development of an effective surface reflection loss model that can approximately account for effects of surface forward scattering in ray-based or mode-based propagation and reverberation codes.

APPROACH

Accurate propagation and reverberation modeling is important for many prediction methods that are important for Navy applications and for underwater acoustics systems development. While acoustic propagation and reverberation modeling has been extensively developed for many years, significant limitations still exist on current capability, particularly in the area of computation speed. In addition, the modeling problem increases in complexity as the frequency is raised from the low frequency region (< 1 kHz) to the mid frequency region (1–10 kHz). At mid frequencies (and higher) the effect of forward scattering from the sea surface and bottom has a greater effect on propagation and reverberation than in the low frequency region, especially in shallow water environments.

The available options for modeling forward scattering in propagation are very limited, and are largely confined to computationally intensive methods that can yield benchmark solutions for certain simplified problems. When PE is used for practical propagation modeling, only large-scale bathymetry variations are included with small-scale boundary roughness ignored, and internal waves are also generally ignored. Even the simple expedient of using a loss at the boundary to approximately account for boundary roughness is not conveniently included in PE propagation simulations. Similarly, normal

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mode methods generally ignore mode coupling due to boundary roughness in forward propagation, and in reverberation simulations only a single scattering (the backscattering) is included. In order to include the stochastic effects of boundary forward scattering and internal wave forward scattering in propagation simulations, investigators have typically applied a full-wave method, such as PE, and performed propagation simulations using many realizations of the fluctuating environment in a “Monte Carlo” approach. Averaging the results over the set of realizations can then give accurate results for averages (or moments) of the field, and by using a sufficient number of realizations even pdfs of field amplitudes or intensities can be obtained. In the case of boundary roughness scattering, simulations using the finite element method have also been used. The computational demands for full-wave Monte Carlo simulations for propagation and particularly for reverberation are severe. Instead of doing time consuming Monte Carlo simulations, much faster solutions for field moments can be obtained if equations governing the evolution of the moments themselves can be obtained and solved. Any method that works with evolution equations for the moments of the propagating quantities can be described as a “transport theory,” though not always referred to as such.

Therefore, the need exists for much faster computational approaches for obtaining moments of the field for propagation and reverberation at mid frequencies that can account for boundary and internal wave scattering. Past work has been restricted to one-way propagation in the range independent case. In the current project this is being extended to range dependent propagation and full reverberation scenarios. Our approach is based on expanding the acoustic field in modes, and therefore would most readily apply at mid-frequencies and below, and in relatively shallow water environments such as on the continental shelf.

We have focused on the case where forward scattering is due to scattering from sea surface roughness. Evolution equations are obtained for the first and second moments of the mode amplitudes, accounting for mode coupling due to scattering from a rough sea surface using first-order perturbation theory [1]. Comparisons with rough surface PE simulations [2] have been used to verify the accuracy of the transport theory method for one-way propagation. It should be kept in mind that transport theory is much faster than full wave approaches that use a Monte Carlo method with many rough surface realizations. Also, any number of forward scattering interactions can be accounted for as the field propagates along the waveguide.

Because transports theory has shown the importance of accounting for sea surface forward scattering in accurately modeling shallow water reverberation at mid frequencies, it becomes imperative to develop as approximate way to include these effects into traditional ray-based or mode-based reverberation codes. A separate project supported by PMW-120 (M. Speckhahn) has been ongoing with this particular goal in mind. The effect of surface forward scattering is treated with an effective surface reflection loss model for the total field (referred to as TOTLOS), where the total field is the combination of the coherent (or reflected) component, and the incoherent (or scattered) component. The original approach in developing TOTLOS was to base it on the results of Monte Carlo rough surface PE results, but as transport theory became available it became clear that results from it were much more suitable to support TOTLOS development. As a result TOTLOS development has become an important secondary goal of the present project.

The approach being used in the development of TOTLOS will be summarized briefly. Because our transport theory is mode-based, it readily provides mode amplitudes as a function of range for any particular shallow water environment of interest. Each mode amplitude can be associated with a particular grazing angle at the sea surface. The decay of each mode amplitude over a cycle distance

(the distance between surface interactions assuming reflected rays) is first determined, and the contribution of loss at the bottom is removed. What remains is identified as a loss in a single surface interaction, and in many cases that loss is negative, which means that there is a gain. In such a case more energy is being forward scattered into a particular mode than is being lost into the bottom in one cycle distance. With this information determined as a function of range for each mode, it is possible to form an effective reflection loss (the TOTLOS model) that will replicate the transport theory results for propagation when surface forward scattering occurs. The model can then be tested in reverberation geometries using TOTLOS in a ray-based code such as CASS-GRAB and making comparisons with transport theory reverberation results.

The TOTLOS model depends not only on the sea surface roughness and frequency, but on range and on the water column and bottom properties, i.e., the TOTLOS model is scenario dependent. To avoid the need to tune the model to each scenario with appropriate transport runs, the approach is to develop an algorithm using quasi-analytic expressions for the model parameters based on a selection of transport runs, and then use that algorithm to define the parameters for the model in general.

WORK COMPLETED

Making data/model comparisons to verify the important effects of forward scattering on mid frequency reverberation levels predicted by transport theory is made difficult by the need for comprehensive environmental characterization of the measurement site, not usually available. Indeed, that need is an important motivation for the basic research reverberation experiment (TREX13) planned for the spring of 2013 near Panama City, Florida. However, the predicted effects are so great that some verification should be possible from existing data sets, though without detailed knowledge of the bottom backscattering strength corresponding to a reverberation data set there can be large modeling uncertainties.

Fortunately, a reverberation data set obtained during ASIAEX in 2001 [3] happens to have properties that allows a test of transport theory predictions while being insensitive to many of the usual modeling uncertainties. Figure 1 is taken from Fig. 9 in [3] and shows the measured normalized reverberation level (NRL) at 2 kHz (left) and 1 kHz (right) on June 3 and June 5, 2001. The normalized reverberation level was obtained by dividing the received level by the energy in the transmitted pulse at 1 m from the source. On June 3 the sea state was relatively low, while on June 5 the wind had increased leading to a higher sea state and a lower reverberation level. Modeling discussed in [3] indicates that bottom reverberation was dominant, and therefore the reduction in reverberation level at the higher sea state was undoubtedly due to the effect of forward scattering from the sea surface. Modeling the normalized reverberation level, even for a very low sea state, would require an accurate model for the bottom backscattering strength. However, for a change in reverberation level as the sea state changes, the sensitivity to the bottom backscattering level, as well as to most other environmenal descriptors, would be largely be removed. The change in reverberation level, shown in the lower panels in Fig. 1, should therefore be able to provide some verification of the accuracy of transport theory for modeling surface forward scattering effects. This verification has been completed and the results are described in the next section.

Transport theory results have also been used to complete an initial version of the TOTLOS model. In this initial version the sound speed profile is assume isovelocity, and a simple surface roughness model has been assumed (an isotropic Pierson-Moskowitz spectrum). The initial version can account for

variations in wind speed, frequency (≤ 3 kHz), and water depth. Future versions will account for more realistic roughness spectra and general sound speed profiles.

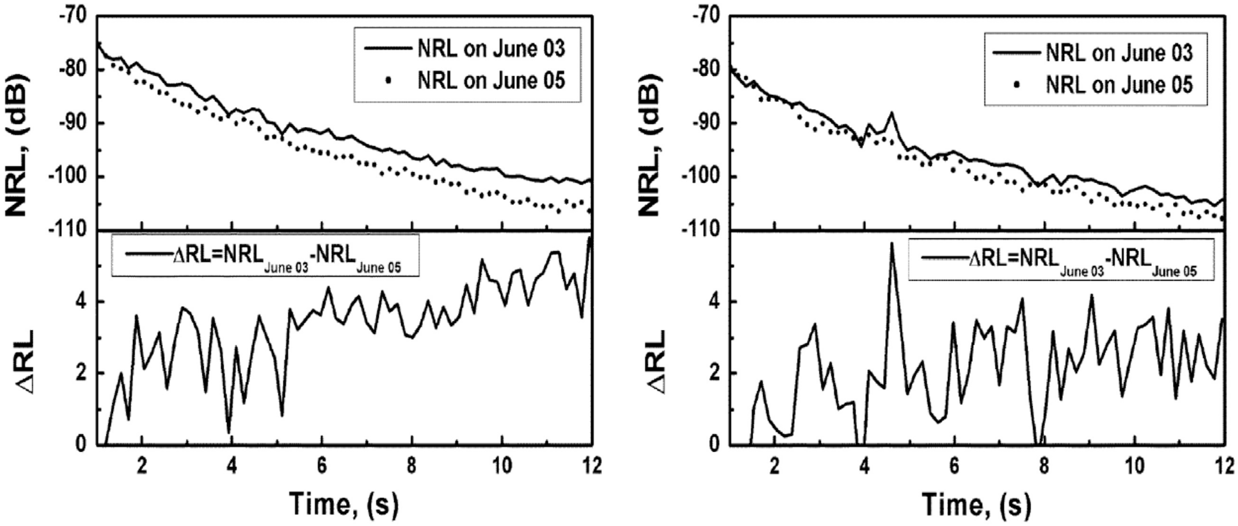

Figure 1. Normalized reverberation levels (NRL) at 2 kHz (left) and 1 kHz (right) measured during ASIAEX [3] at the same site on two different days. The higher sea state on June 5, 2001 led to lower reverberation levels, which were known to be dominated by bottom reverberation.

RESULTS

Before discussing the reverberation difference for the ASIAEX case, it is worthwhile to mention some background using a figure given in the report for FY11, reproduced here in Fig. 2. For the reverberation example in Fig. 2 the frequency is 3 kHz, the rough sea surface is modeled with an isotropic Pierson-Moskowitz roughness spectrum for a wind speed of 7.7 m/s giving an rms wave height of 0.31 m, the sound speed is taken as isovelocity at 1500 m/s, and the bottom roughness is described by the Reverberation Modeling Workshop “typical roughness” model [4]. Additional description of the parameters in this example can be found in the FY11 report.

Figure 2 shows two sets of reverberation curves out to a time of 60 s, the lower set of three curves is for surface reverberation only, and the upper set is for surface and bottom reverberation. For the lower set the bottom is taken as flat with no roughness. It is evident for this isovelocity case with typical surface and bottom roughness that bottom reverberation is dominant and the surface contribution can be neglected. The upper set of curves can be considered due to bottom reverberation alone. There are three ways of modeling the reverberation: ignore effects of surface forward scattering (red curve), use the coherent reflection loss for the surface interaction (green curve), and fully account for the effects of forward scattering with transport theory (blue curve). The differences between the three ways of modeling the reverberation are significant and can exceed 10 dB for this example. For the ASIAEX example the frequency is lower and the surface forward scattering effects are less but still significant. When considering the ASIAEX example the same three ways of modeling the reverberation will be considered and applied to the reverberation difference between the two sea states represented in Fig. 1.

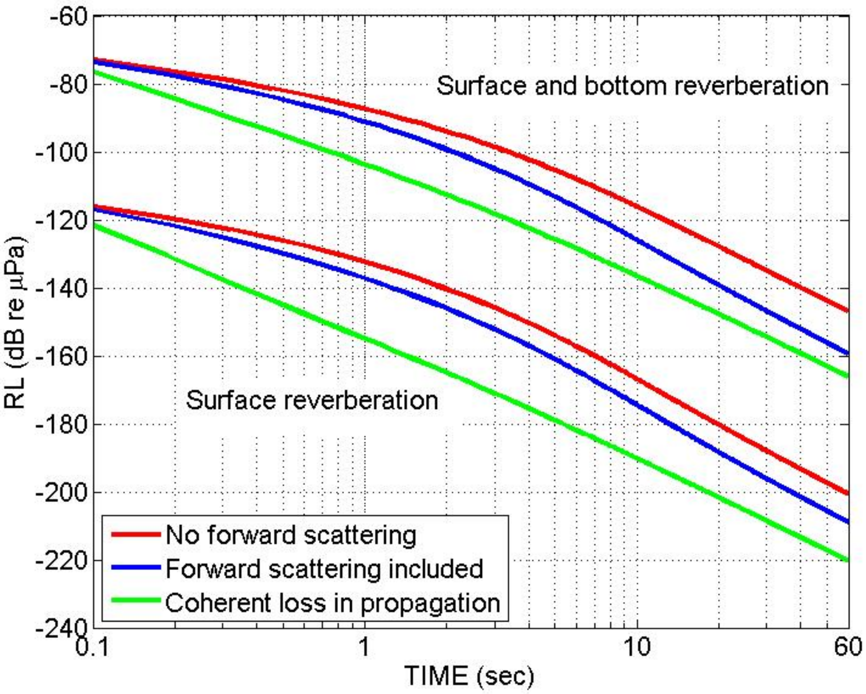

Figure 2. Reverberation predictions at 3 kHz obtained with transport theory. The red curves ignore all effects of boundary roughness during propagation. The blue curves account for surface forward scattering. The green curves approximate the effect of surface forward scattering in terms of a coherent loss.

Because reverberation difference will be less sensitive to the environmental details, approximations can be made when modeling the lower panels in Fig. 1. On June 3 the wind speed is reported [3] as 3 m/s with an rms wave height of 0.1 m, and on June 5 the wind speed is reported as 9 m/s with an rms wave height of 0.35 m. Because both the explosive source and single hydrophone receiver can be considered a point source or receiver, the contributions to reverberation arise from a circular annulus, and directional aspects of the wave field will not be very significant. Thus, the surface roughness is modeled with the same isotropic Pierson-Moskowitz model used for Fig. 2 with the wind speed chosen to yield the reported wave heights. With this choice, the wind speed used for June 3 is 4.33 m/s and for June 5 is 8.10 m/s. The sound speed profile (Fig. 2 in [3]) was not perfectly isovelocity, but is approximated as isovelocity for the purpose of this comparison. The source and receiver depths are given in [3] as 50 m and 90 m, respectively. Bathymetry data at the site [5] indicate that use of an average water depth of 110 m is a reasonable approximation. The values for water and sediment sound speed, and sediment density and attenuation are as described in [3].

The measured reverberation differences [6] are compared with transport theory results in Figs. 3 and 4 for a frequency of 1 kHz and 2 kHz, respectively. If effects of surface forward scattering were ignored completely, corresponding to the red curves in Fig. 2, the differences in Figs. 3 and 4 would be 0 dB for all times (not plotted). If surface forward scattering were treated using the coherent reflection loss, corresponding to the green curves in Fig. 2 (using the first moment with transport theory), the predicted reverberation difference is given by the green curves in Figs. 3 and 4, showing greater

differences than observed between the two sea state conditions. Finally, if surface forward scattering were treated in detail with transport theory (using the second moment with transport theory), the result is given by the blue curves, in remarkably good agreement with the data.

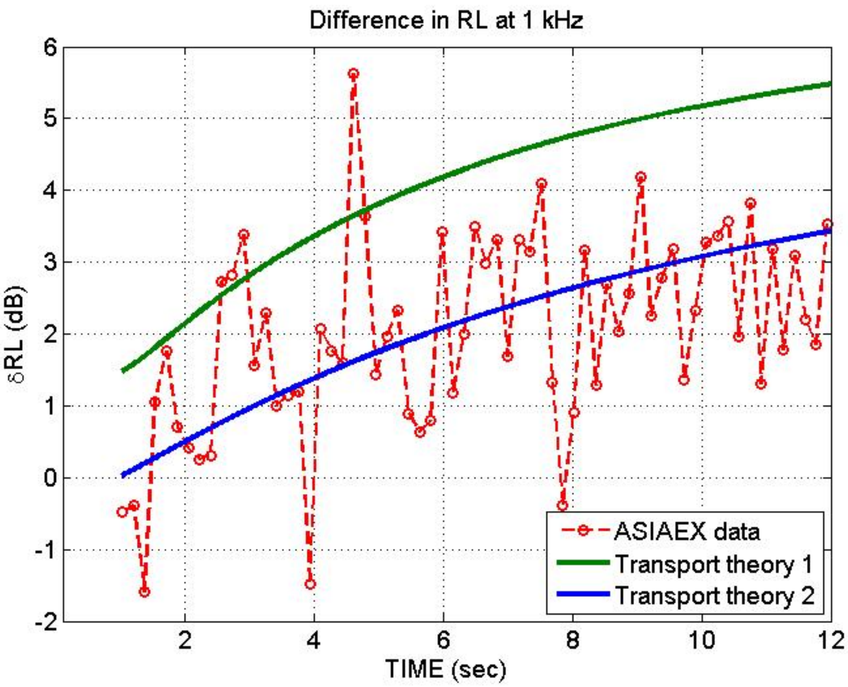

Figure3. Data/model comparison for reverberation difference between June 3 and 5, 2001. The green curve assumes a coherent loss at the surface, while the blue curve accounts for forward scattering.

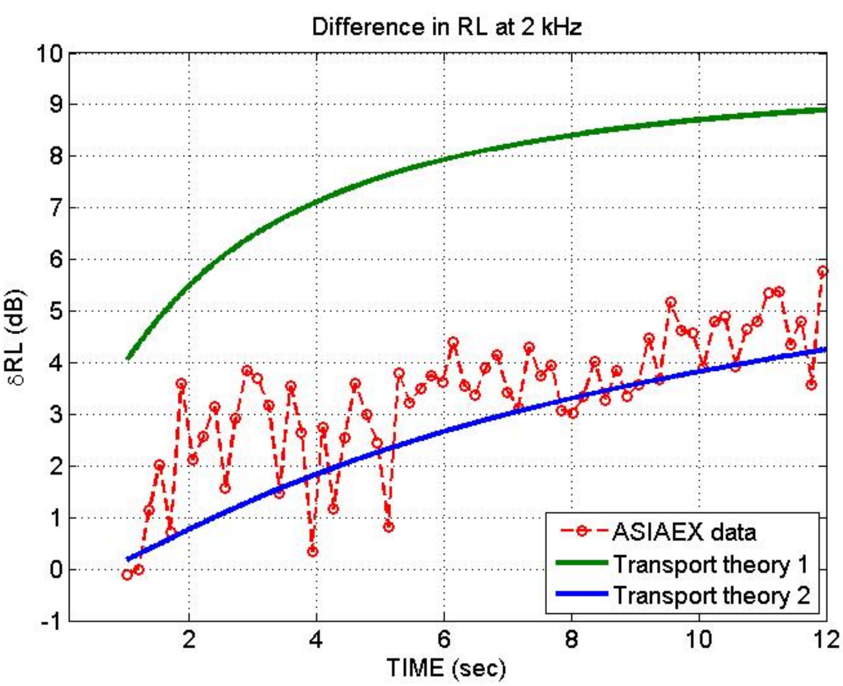

Figure 4. Same as Fig. 3 but for 2 kHz.

If must be appreciated that the transport theory results shown in Figs. 3 and 4 are completely constrained by the environmental conditions, the geometry, and the reasonable simplifying assumptions made. There were no degrees of freedom available to improve the agreement. This data/model comparison supplies a very satisfactory verification of the important effects of forward scattering in the mid frequency region for these relatively modest sea conditions at 1 and 2 kHz. Figure 2 indicates that at 3 kHz the magnitude of these effects is significantly greater. One goal for TREX13 is to obtain data sets for verification of these effects up to 3 kHz using absolute level comparisons, that is, not utilizing reverberation differences to reduce sensitivity to environmental conditions.

IMPACT/APPLICATIONS

Work in transport theory propagation and reverberation modeling should lead to improved simulation capability for shallow water propagation and reverberation in which multiple scattering from rough boundaries is properly taken into account. This capability should be particularly important in the mid-frequency range where multiple scattering effects can be important, yet where a modal description can be used. Transport theory propagation and reverberation modeling has the potential to be even faster than ray tracing, yet be able to account for scattering effects outside the scope of other efficient modeling methods.

RELATED PROJECTS

1. Reverberation Modeling Workshops, Eric Thorsos and John Perkins co-chairs. This effort has developed a set of well-define reverberation problems with consensus solutions. This has been important for testing the accuracy of transport theory for reverberation problems when forward scattering is ignored as assumed for the workshop problems.

2. ONR (John Tague) is supporting work on extending the Sonar Simulation Toolset (SST, development under the direction of Bob Goddard, APL-UW) to lower frequencies. A PE based reverberation model is presently being developed for SST for the low frequency extension. A future possibility of utilizing transport theory propagation has been discussed in this context, with the proviso that it first requires additional development.

3. PMW-120 (Marcus Speckhahn) is supporting work on developing a model (TOTLOS) that can approximately account for effects of surface forward scattering in ray-based (such as CASS/GRAB) or mode-based propagation and reverberation models. Results for transport theory are now being used to aid in TOTLOS development, which has become an important component of the present project.

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